

The long hot summer of the tokamak

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Abstract

What have the probability for fine weather in summer and the possibility for a future use of nuclear fusion as a practically unlimited and clean energy source got in common? The answer is in the particular nature underlying both physical systems: both the atmosphere and hot magnetized fusion plasmas are determined by similar processes of structure formation in quasi-two-dimensional periodic nonlinear dynamical systems. Self-organization of waves and vortices on small scales in both cases leads to large-scale flows, which are, depending on conditions, either stable for a long time - or can break apart intermittently and expel large vortex structures. In the case of earth's atmosphere, a potential stabilization of the polar jet stream over northern Europe by warming in early summer leads to a high probability for stable hot midsummer weather in central Europe. The efficient utilization of nuclear fusion in a power plant also depends if a stabilization of such zonal flows ("H mode") may be sustained by heating of the plasma. However, instabilities may ruin by rain European summer holidays ("icelandic lows"), as well as lead to tempestuous eruptions ("ELMs") of energy and particles from the edge of a fusion plasma onto the walls of the reactor. In the latter case, this could cause strong erosion of the wall materials and thus an unefficient operation of a future fusion power plant. Plasma physicists are - similar to meteorologists - therefore interested in accurate predictions of these strongly nonlinear dynamical processes.

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I. ZONAL FLOWS AND THE H-MODE

Present fusion experiments and future fusion power plants rely on operation in a high-confinement H mode [1–3]. The H mode state is characterised by an edge transport barrier related to a radial electric field E_r in the outer closed flux surface region, which induces a perpendicular flow with the $E \times B$ velocity. A sheared flow arising from a radial variation $E_r(r)$ is invoked to explain the transport barrier through a suppression of turbulent transport [2, 4, 5]: small-scale turbulent vortices are tilted or sheared apart by the shear flow vorticity, so that the Reynolds stress transfers energy from the vortices to the mean flow [6, 7]. A flow shear layer can thus be enhanced by turbulence (which in turn it suppresses), but can also be caused by neoclassical equilibrium electric fields [8, 9].

In contrast to such mean $E \times B$ flows, also fluctuating zonal flows and their interaction with turbulence play an important role in regulating tokamak and stellarator edge plasma transport [10]. Zonal flows appear through turbulent self organisation of quasi 2-d fluids like magnetised plasmas [11], or in geophysical, planetary and stellar atmospherical and oceanic dynamics [12–14]. Zonal flows may be interpreted as a low-frequency spectral condensate phase of the turbulence [10, 15] that possesses the highest symmetry possible in the given geometry: atmospherical and oceanic zonal jets are latitudinal, and zonal modes in toroidal fusion plasmas are perpendicular to the magnetic field on flux surfaces. The transition between low (L) confinement to the high (H) confinement mode, which in general occurs in divertor tokamaks after a threshold heating power is exceeded, can not yet be explained by any theory with predictive quality or by any first-principles (turbulence) based numerical simulation [16]. Some descriptive models regard the transition as a predator-prey type bifurcation, where the turbulence driven zonal flows in turn suppress and self-regulate the turbulence and transport [17]. Toroidal turbulence simulations indicate that the self-consistent zonal flows indeed significantly moderate but never completely suppress the turbulence [18].

Edge localised modes (ELMs) are quasi-periodic eruptions from the edge of H mode plasmas [19–21]. The ELM burst leads to enhanced transport and of heat and particles into the open scrape-off layer field line region and on to the divertor plates [22]. Some type (III) of ELMs show similarities to bursts in the flow equilibrium found in global computations of drift wave turbulence [23, 24], while an other type (I) is assumed to be related to the ideal ballooning mode instability [20] and subsequent enhanced turbulent transport [25].

II. JET STREAMS AND THE SEVEN SLEEPERS

There is a remarkable analogy between the H mode in tokamaks and the “Seven Sleepers” summer weather phenomenon occurring in some regions of central Europe. In both cases stabilised zonal flows act as transport barriers in a quasi two-dimensional system.

Jet streams are strong latitudinally extended and narrow flows in the upper atmosphere that are determined by Rossby wave interaction similar to drift wave coupling to plasma zonal flows [12]. The similarity in the underlying quasi two-dimensional fluid dynamics is expressed in the isomorphism between the Charney-Obukhov equation for baroclinic dynamics in a rotating system [26, 27] and the Hasegawa-Mima equation for turbulence in magnetised plasmas [28, 29]. Jet streams have a considerable influence on the weather conditions and short term weather development, and in turn are affected by the dynamics of rotating weather fronts [30]. They also couple to oceanic streams and oscillations. While the jet stream zonal flows often appear undulated and broken, they may stabilise over a period of a few days, and sometimes, but much more rarely, even over a few weeks. A prominent example is the possibility for stabilisation of the northern polar jet stream in summer, which can result in a stable weather period over central Europa for a few weeks that usually starts in early July. This phenomenon is resembled in the southern German “Siebenschläfer” farmer’s weather lore “*Das Wetter am Siebenschläfertag sieben Wochen bleiben mag*”: the weather condition around the Seven Sleepers day (June 27) might persist for seven weeks. This weather forecasting day is by lore supposed to be on the day devoted in Christian calendars to the “Seven Sleepers” of Ephesus patron saint legend [31].

Indeed a statistically significant meteorological summer singularity is noted to occur in central Europe with the key date in the first week of July (around July 7): if the northern jet stream has stabilised at that days, then with some probability it will remain in its position and stabilise the general weather situation in central Europe for some time between two and eight weeks. If the jet stream is located far north (over Scotland and Scandinavia) then troughs of the Icelandic Low are prevented to propagate into central Europe, and warm, dry and sunny weather determined by the Azores High will prevail. If the jet stream position is located more to the south (across central Europe) or (unfavourably) meridionally broken, then the Icelandic Low will carry cool and wet conditions further south to regions ranging from southern France, Switzerland to southern Germany and further, mostly limited

by the Alpine barrier. Then another formulation of the farmer’s lore is appropriate: “*Ist Siebenschläfer nass, regnet’s ohne Unterlass*”: if it is wet at Seven Sleepers, it will go on raining without cease.

According to the German Meteorological Service, the lore is statistically well established in southern Germany, where it has originated, and tends to cease to apply further in the north [32]: In the Munich region in southern Bavaria and around Innsbruck in Austria the *Siebenschläfer* rule has a predictive quality of up to 80 %, i.e. it works well in around four of five years. The predictability decreases to around 60-70 % further north towards to the middle of Germany (Frankfurt), and at a latitude corresponding to Hamburg or London it has shrunk to around only 50 %. Note that this is not the probability for fine weather, but for persistence of the general weather situation after the singularity.

While some weather singularities may change or diminish over time (e.g. the former Alpine regional “Schafskälte” cool weather snap in middle of June appears not to apply any more in recent decades [33]), the *Siebenschläfer* rule seems to be a long term weather phenomenon: the apparent deviation of the singularity date by 10 days (July 7 instead of June 27) is generally assumed to correspond to the change from Julian to Gregorian calendar in the 16th and 17th century. The *Siebenschläfer* rule thus appears to be at least half a millennium old, and still applies. Similar summer weather lore is known from other regions, like St. Swithun’s day (July 15) in the British Isles, or Saint-Gervais et Saint-Protas day (June 19) in France, or St. Godelieve’s day (July 6) in Belgium [34]. The predictability quality of these otherwise similar farmer’s rules is however usually lower than for the *Siebenschläfer* rule around south Germany. There are a number of further weather rules corresponding to established weather singularities in some regions around the world, although the majority of farmer’s weather rules are generally not trustworthy [31].

The formation and location of the summer norther polar jet stream is linked to the warming of the northern atmosphere in spring and early summer. The zonal flow stabilisation of the summer weather is most noticeable in the years with a hot and dry period. On most occasions the more stable jet stream dominated period lasts up to around four weeks [35] and is often terminated by south-western disturbances, but may sometimes last a few weeks longer. The latest of such a “quiescent H mode summer” has occurred in 2003. In more recent years the rule also often had applied correctly in the southern German and Austrian area, but has mostly led to a continuation of prevailing unstable conditions throughout these “L

mode” summers. Then warm periods of a few days have often been consecutively interrupted (on a nearly weekly basis) by cooling thunderstorm fronts. Notably, the average summer temperature still has risen over the last years, whereas humidity and rain fall have been increased in such “Type III ELMy H mode” years, like in 2011. The coupling between jet stream activity and global warming is in any case highly nonlinear and future developments in this complex dynamical system are hardly predictable. There appears to be a trend towards a poleward shift of the jet streams over the last decades: while the subtropical northern jet stream tends to become weaker, the statistics suggest some trend towards strengthening of the northern polar stream [36].

III. OUTLOOK AND CONCLUSIONS

The quasi two-dimensional fluid systems of the earth atmospherical dynamics and of magnetised plasma turbulence feature some remarkable analogies, starting from the isomorphic description in the most simple (but of course for practical application too much oversimplified) constituting equations, and showing some similar large-scale structure formation processes, like the coupling between eddy motion with zonal flows.

The zonal flows in tokamaks and the atmospheric jet streams are under certain and in both cases not yet completely understood conditions (controlled by heating) able to stabilize into long term mean flows that can act as transport barriers on small scale eddy motions.

Both the fusion plasmas as well as the weather dynamics are highly nonlinear and complex dynamical systems, which are not (yet) on the long term predictable by any first principles based theory or simulation. Experience has in both cases lead to heuristic rules that allow for some statistical prognosis. Scaling laws derived from existing tokamak experiments lead to a prediction of a 70-90 % chance that the next international fusion experiment ITER will operate in an H mode state (or more specifically, to reach a fusion efficiency of $Q_0 \geq 10$) [37]. Weather recordings lead to a prediction that the next summer in Innsbruck will have an 80 % chance to persist in the same large weather situation (whatever this will be) as in the first week of July. This is usually a good basis for planning further summer vacations. And, altogether, these are good reasons to further continue with fusion plasma physics research in general, and with our quest to understand turbulence and predict the H mode in particular.

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